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A tunable UV and IR laser source was purchased through this grant, utilized in lidar experiments and evaluated for potential DOD applications. The laser technology was incorporated into the HU ozone differential absorption lidar system and lidar measurements of ozone were made. This same technology approach was utilized in the design of the laser for the HU scanning eyesafe aerosol lidar system. This effort resulted in a second research proposal being submitted jointly by HU and ITT Industries with AFRL support to apply this technology to the problem of laser induced fluorescence detection of bioaerosols for airbase defense.

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Tunable Ultraviolet and Infrared Laser Source for Student Lidar Experiments

Final Report

Introduction: Project Objectives

As described in the original proposal, the goal of this instrumentation proposal is to outfit the Laser Development and Lidar Applications Laboratory in the Hampton University Physics Department with a state-of-the-art tunable optical parametric oscillator (OPO) laser system. This laser will replace inferior equipment on temporary loan from NASA. In conjunction with diagnostic equipment and UV and IR lidar systems already available in the Laboratory, it will enable a variety of experiments in laser physics and remote sensing to be performed by Hampton University undergraduate and graduate students. The remote sensing experiments that this laser system will make possible will involve students from a variety of departments, including physics, electrical engineering, computer science, chemistry, mathematics, and biology. Finally, this laser system will increase the capability of the Hampton University to contribute to the ongoing DOD program to remotely detect hazardous biological agents.

The experiments listed in the proposal to be conducted with this laser include: (1) evaluation of the laser as a tunable UV source for lidar LIF (laser induced fluorescence) measurements of biological warfare agents, (2) integration into the existing HU UV differential absorption ozone lidar system to improve upon and replace the laser transmitter currently on loan from NASA and laboratory testing of this system, (3) field measurements of tropospheric ozone with this system, (4) eye-safe detection of clouds and aerosols in the infrared with HU's IR lidar receiver, (5) evaluation as a laser source for trace gas sensing in the near IR, and (6) evaluation as a high power eyesafe second generation source for incorporation into HU's scanning aerosol system currently being designed by the multidisciplinary student team in HU's new Center for Lidar Atmospheric Science Students (CLASS).

Through the involvement of underrepresented minority undergraduate and graduate students in these laser experiments and lidar measurements, the project will increase the number of highly-trained minority students in graduate science and engineering programs. As a direct consequence of these student projects and through subsequent follow-on projects to build and test a complete LIF lidar system, Hampton University students and faculty will be better able to contribute to the DOD's ongoing research program in the remote detection of battlefield biological agents. In addition, this laser system will be invaluable for the development of other current and future laser and remote sensing projects at Hampton University

Technical Approach

To achieve these goals, the project leveraged internal laser research and development by ITT Industries, Advanced Engineering and Sciences Division ($50,000) along with ITT

cost sharing on this effort ($10,200) with funding from three NASA education and research training grants: one to develop and field an ultraviolet ozone lidar system for $360,000/ 2years (and its follow-on grant, for $200,000/2years), and the second to design and build an eyesafe aerosol lidar system operating at 1.5 microns (the Center for Lidar and Atmospheric Sciences Students (CLASS) grant for $2,500,000/5 years). All these grants support student research training in lidar, optical physics, remote sensing, and computer technology.

The laser development effort supported by these other grants and supported in part through this infrastructure grant, as well as the final laser system delivered under this infrastructure grant are described in an article published in the Proceedings of the IEEE Aerospace Conference, reprinted as Appendix 1 of this report. The laser technology performed extremely well. It was described in an article by Steve Moody concerning state of the art lidar systems in Photonics Spectra in October 1999 (Appendix 2). Furthermore, it was decided to incorporate the results of this development directly into the first generation 1.5 micron laser transmitter for the CLASS scanning lidar rather than the second generation laser for this system as originally proposed. Thus, this infrastructure support grant has enabled HU to leverage other funds to purchase two new state of the art laser transmitters, one optimized for UV generation for the ozone lidar system, and one optimized for 1.5 micron generation for the CLASS aerosol system.

Evaluation of the Laser Source for UV LIF detection of Biological Warfare Agents

The laboratory evaluation of the OPO laser source described in Appendix 1 yielded extremely promising results, including conversion efficiencies to the UV close to twice that of present dye laser systems. A theoretical evaluation of a UV LIF/eyesafe cloud detection system based on a high power version of the laser was undertaken jointly with ITT and culminated in a proposal, "High Peak Power Tunable Laser for Remote Detection of Bioagent Clouds" submitted to the FY00 Defense University Research Instrumentation Program by Hampton University. In brief, numerical calculations indicated that the performance of the proposed system would be 10-20 times more sensitive than the current SR-BSDS (Short Range Biological Standoff Detection System) being tested by the Army. Despite a strong letter of support from Lt. Col. Christopher Washer at AFRL, who is interested in developing this technology to protect airbases from bioagent attack, the proposal was not funded.

Laser Transmitter for HU's Compact Ozone Lidar System

The second objective in this project was to replace the inferior, borrowed laser source in the HU compact ozone DIAL system with a UV laser funded through this infrastructure grant. This was successfully accomplished. The purchased laser is shown schematically in figure 1. A description of the ozone lidar system is presented in Appendix 3, which is a reprint of a paper accepted for presentation at the 20th International Laser Radar Conference in July, 2000.

Eyesafety considerations limit the pulse energy to ~8 mJ for our ozone system for either 20 or 30 Hz. Therefore, to maximize the transmitted eyesafe power, it was decided to

utilize a 30 Hz pump laser rather than a 20 Hz laser. This OPO laser, configured as in the lidar transceiver box, is shown in figure 1. We mix the output wavelengths of singly resonant IR Type II KTA OPO's with the 355-nm output of a frequency-tripled Nd:YAG laser. The OPO's are pumped by 80 mJ of the 1064-nm fundamental wavelength from the injection-seeded Nd:YAG laser and are operated at 1.55 and 1.91 microns. The pump beam diameter is 4 mm. The tripler provides approximately 50 mJ of uv into the mixer. The resulting uv output energy from the mixers have been measured to be approximately 8 mJ for both 289 nm and 299 nm, corresponding to an overall conversion efficiency of 3%. The divergence of the uv output is approximately the same as the 355 nm beam (~1 mrad full angle) and the uv linewidth is under 0.2 nm (instrumentation limited). Prior to transmission from the lidar system, the uv beam is expanded to be eyesafe.

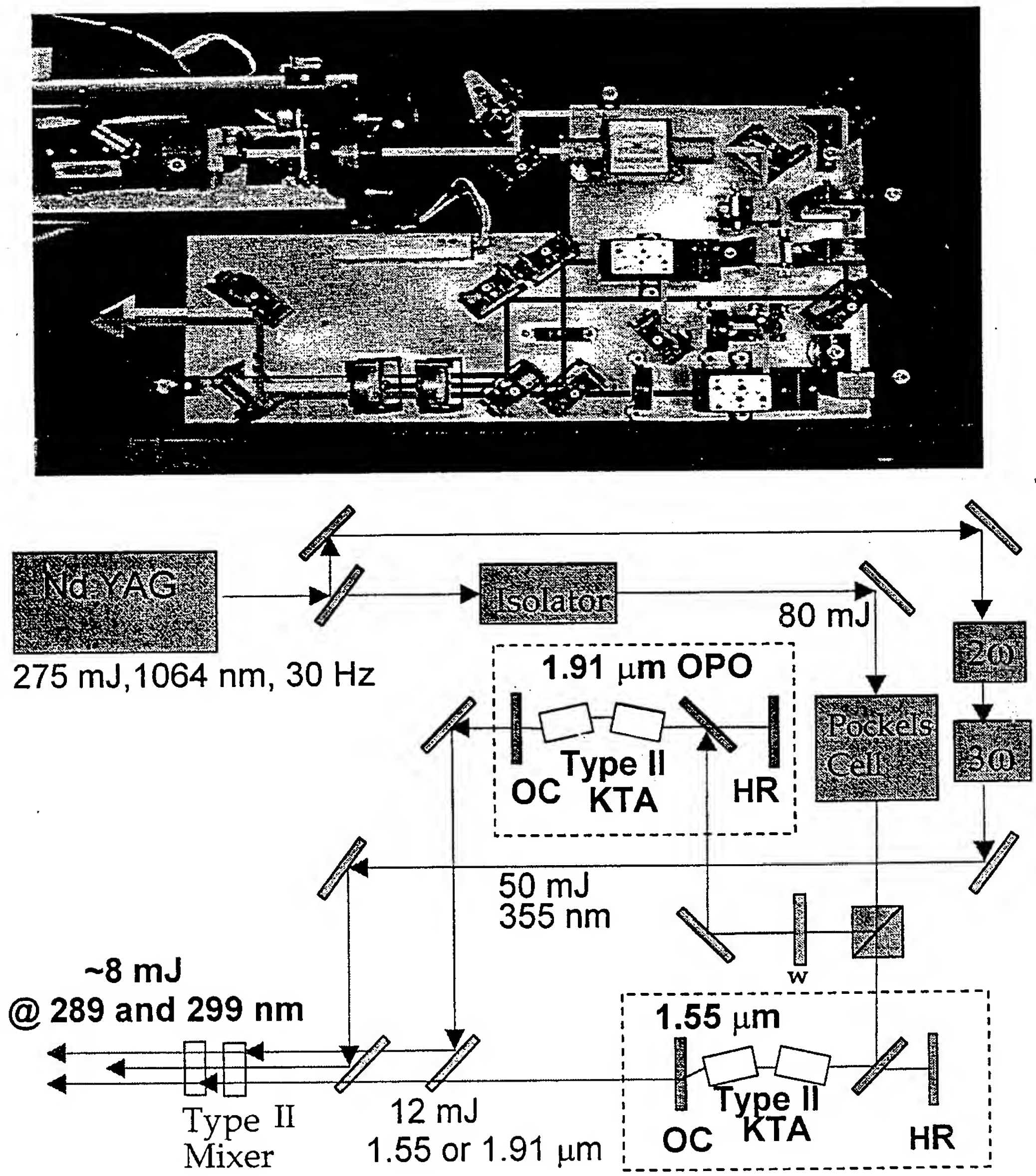

Figure 1. The ozone lidar transmitter purchased through the infrastructure grant

Field Measurements of Tropospheric Ozone with the Lidar System

The ozone lidar system was ground tested during June, 2000, and the first preliminary measurements of ozone were made. A number of laser and receiver improvements, data acquisition software modifications and further tests were seen to be necessary. Replacement components were ordered and will be implemented this fall during the second round of system tests. We have attempted to compute atmospheric ozone from our first set of on-line and off-line measurements. The 289 nm and 299 nm lidar returns are shown in figure 2 together with the resulting ozone mixing ratio. No Rayleigh or aerosol correction terms have been included in these calculations. It should be noted that only 1 second time averages (30 shots) were possible at the time these measurements were made. Numerical simulations show that time averages of tens of minutes are necessary with these low energies. The range cell size is 75 meters. Laser energies were 4-6 mJ. A series of on-line returns were first taken followed by a set of off-line returns; it was not possible to interleave the wavelengths during these measurements. The detector channel used was the near field (A-D) channel. Reasonable ozone levels are seen between 500 m and 1 km. The unreasonably high ozone levels at low altitude and highest altitudes are probably due to differences in the on-line and off-line laser-FOV alignments. During the coming year, the lidar system will be improved and additional measurements made. Ms. Brandi Thomas and Ms. Crystal Toppin, BS graduates in physics, assisted in writing LabVIEW software for this project. Ms. Renee Payne, 2nd year physics graduate student, will use this laser source in her Ph.D. research project on the ozone lidar system. Renee visited ITT in November of 1999 and in March of 2000 to learn first-hand about the operation of the OPO laser source.

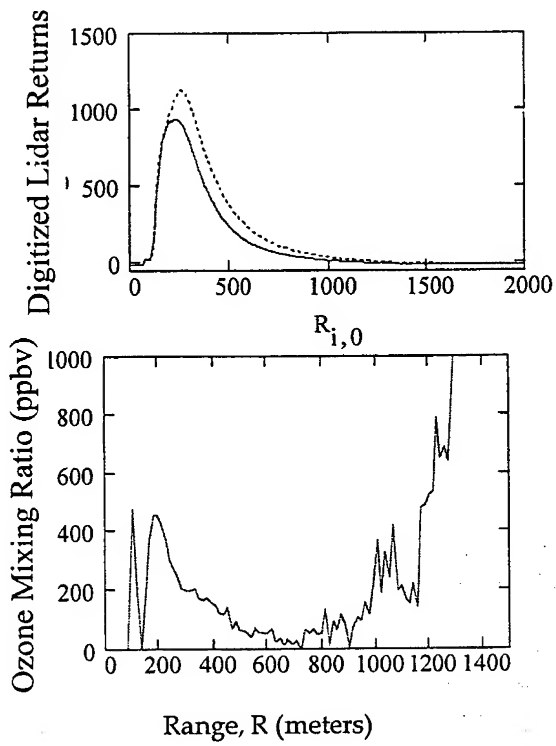

Figure 2: DIAL returns and computed ozone mixing ratio (ppbv)

Eye-safe Detection of Clouds and Aerosols in the Infrared with HU's IR lidar Receiver

The decision to incorporate the 1.5 micron OPO technology into the first generation CLASS aerosol lidar system precluded the possibility of performing this proposed experiment with the existing IR lidar receiver due to lack of time. Rather, it was felt that

the best use of manpower is to use the CLASS aerosol lidar system (incorporating this new laser technology) to make these measurements during this academic year.

Evaluation as a laser source for trace gas sensing in the near IR

In the proposal, it was stated that the laser source could possibly be injection-seeded by the existing low-power commercial OPO system currently at HU and thereby tested as a high power narrowband laser source. It has been decided that a higher priority is to use the laser as a dedicated transmitter for the ozone lidar system and not to try to modify it at this time for this other experiment. However, the addition of a KTA optical parametric amplifier (OPA) stage to the low power commercial OPO is presently being evaluated. It is expected that this will be purchased from ITT through funding from other current grants. This OPA stage is based on the same technology as the OPO funded through this infrastructure grant. This would contribute to the Ph.D. research of Sangwoo Lee who is currently remotely detecting trace gases with the low power narrowband laser system.

Evaluation as a high power eyesafe second generation source for incorporation into HU's scanning aerosol system

As previously mentioned, the impressive performance of the OPO system being purchased under this grant led to the incorporation of this technology immediately into the first generation lidar transmitter for the CLASS aerosol system, rather than as a 2nd generation upgrade for the lidar. The resulting scanning aerosol lidar system is described in Appendix 4, which is a reprint of a paper presented at the 20th International Laser Radar Conference. The CLASS students participating in the project are listed as coauthors on the paper. Subsequent to the time this article was drafted, the aerosol transceiver box was mounted into the lidar scanner. Figure 4 shows the CLASS lidar system from the front and figure 5 shows the system with the rear cover removed to

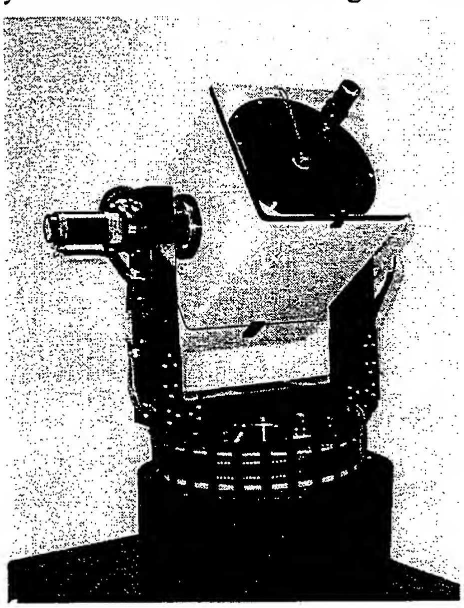

Figure 4. The CLASS scanning lidar.

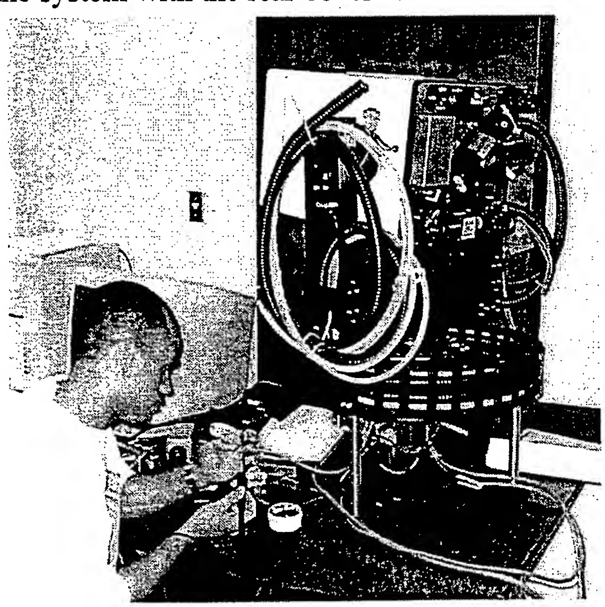

Figure 5. Russell Battle (HU, EE) working on the lidar with the rear panel removed, revealing the OPO laser transmitter.

reveal the OPO laser.

Conclusion

This report has demonstrated that the DOD Infrastructure Support Grant has had a major impact upon the education and research training of HU students. It has enabled two of HU's lidar systems to incorporate state-of-the-art laser technology. An optical parametric amplifier stage, based on this technology, is being evaluated for incorporation into a third lidar system. A study and research proposal was drafted jointly with ITT and endorsed by personnel at AFRL to develop a high power version of this laser for UV LIF detection of hazardous bioagent clouds. Unfortunately this proposal was not funded.

With the publication of atmospheric measurements acquired with these laser systems, it is anticipated that HU will be in a stronger position to compete for future funding opportunities from the DOD and to make a significant contribution to addressing the atmospheric remote sensing needs of our armed services.

The following students have participated over the past year or are currently participating in lidar projects which utilize the laser technology supplied or developed under this grant:

- Renee Payne-Baggott, Ph.D. physics graduate student, ozone lidar project
- Brandi Thomas, B.S. physics, ozone lidar project (now with Torch Technologies)
- Crystal Toppin, B.S. physics, ozone lidar project (now at U. Wisconsin, Milwaukee in graduate school in physics)
- Lincoln Haughton, B.A. Mathematics, CLASS aerosol lidar project (now with Lockheed Martin who will pay for his graduate work in applied mathematics)
- Ann Futrell, Mathematics student, CLASS aerosol lidar project
- Belicia Bradley, B.A. Mathematics, CLASS aerosol lidar project (now at Harvard graduate school in mathematics)
- Kelley Reaves, Computer Science graduate student, CLASS project
- Rashan Patterson, EE, CLASS aerosol lidar project
- Kyle Lewis, EE, CLASS aerosol lidar project
- Demetra Johnson, Chem E., CLASS aerosol lidar project
- Chadwick Giles, Chem E., CLASS aerosol lidar project
- John Davis, Chem E., CLASS aerosol lidar project
- Russell Battle, EE, CLASS aerosol lidar project
- Clarence Glenn, Chem., CLASS aerosol lidar project
- Nasira Latif, physics, CLASS aerosol lidar project
- Langdon Williams, physics, CLASS aerosol lidar project
- Mika Edmondson, physics, CLASS aerosol lidar project
- Ayana Jordan, biology, CLASS aerosol lidar project
- Crystal Meyer, biology, CLASS aerosol lidar project

All of these students are African American U.S. citizens.

Publications and presentations arising from projects incorporating laser technology obtained through this grant (student names in boldface)

Conference and Science Meeting Presentations by Students:.

- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton**, SEMS Research Seminar, Hampton University, Hampton, Va., December 3, 1999.
- "Ozone Altitude Profile Analysis for the Ozone Lidar Project," **B. Thomas, C. Toppin**, D. Harper, T. Zenker, and T. H. Chyba, 5th Annual Hampton University Student Research Symposium, Hampton, Va., February 5, 2000.
- "The CLASS Aerosol Lidar Project," **B. Bradley, A. Futrell, L. Haughton, K. Lewis, R. Patterson, C. Glenn, K. Reaves, C. Meyer, L. Samuel**, A. Bowman, **L. Williams, M. Edmondson, S. W. Lee, R. Payne**, S. Bailey, A. Omar, D. A. Temple, T. H. Chyba, N. S. Higdon and D. A. Richter, 5th Annual Hampton University Student Research Symposium, Hampton, Va., February 5, 2000.
- "Laser Eyesafety Calculations for Lidar Systems," **M. Edmondson**, T. H. Chyba, N. S. Higdon and D. A. Richter, 5th Annual Hampton University Student Research Symposium, Hampton, Va., February 5, 2000.
- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton, A. Futrell**, D. A. Temple, and T. H. Chyba, 5th Annual Hampton University Student Research Symposium, Hampton, Va., February 5, 2000.
- "Data Acquisition, Analysis and Storage in an Aerosol Lidar System," **K. Lewis, R. Patterson, K. Reaves, B. Bradley**, D. A. Temple, and T. H. Chyba, 5th Annual Hampton University Student Research Symposium, Hampton, Va., February 5, 2000.
- "Atmospheric Absorption and Laser Wavelength Selection," **C. Glenn**, A. Omar, D. A. Temple, and T. H. Chyba, CLASS Site Visit, Hampton University, Hampton, Va., February 10, 2000.
- "Lidar Receiver Design and Evaluation," **K. M. Lewis**, CLASS Site Visit, Hampton University, Hampton, Va., February 10, 2000.
- "Data Acquisition, Analysis and Storage in an Aerosol Lidar System," **K. Lewis, R. Patterson, K. Reaves, B. Bradley**, D. A. Temple, and T. H. Chyba, CLASS Site Visit, Hampton University, Hampton, Va., February 10, 2000.
- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton, A. Futrell**, D. A. Temple, and T. H. Chyba, CLASS Site Visit, Hampton University, Hampton, Va., February 10, 2000.
- "Laser Eyesafety Calculations for Lidar Systems," **M. Edmondson**, D. A. Temple, T. H. Chyba, N. S. Higdon and D. A. Richter, CLASS Site Visit, Hampton University, Hampton, Va., February 10, 2000.
- "Ozone Altitude Profile Analysis for the Ozone Lidar Project," **C. Toppin**, T. Zenker, and T. H. Chyba, Virginia Space Grant Consortium Student Research Conference, NASA Langley Research Center, Hampton, Va., March 24, 2000.
- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton**, D. A. Temple and T. H. Chyba, Senior Mathematics Seminar, Hampton University, Hampton, Va., April 4, 2000.
- "Laser Eyesafety Calculations for Lidar Systems," **M. Edmondson**, T. H. Chyba, N. S. Higdon and D. A. Richter, Beta Kappa Chi 57th Annual Meeting , Nashville, Tn. April 7, 2000
- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton**, D. A. Temple and T. H. Chyba, Beta Kappa Chi 57th Annual Meeting , Nashville, Tn. April 7, 2000.
- "Mathematical Modelling of an Aerosol Lidar System," **L. Haughton, A. Futrell**, D. A. Temple and T. H. Chyba, National Council of Undergraduate Research Annual Meeting, Missoula, Mt., April 28, 2000.

Conference and Science Meeting Presentations by Faculty:

- "Tunable UV generation with a frequency-mixed Type II OPO," D. A. Richter, W. D. Marsh, N. S. Higdon, T. H. Chyba, and T. Zenker, IEEE Aerospace Laser Conference, Big Sky Montana, March 20-24, 2000, paper 240.

- "The CLASS Project," D. A. Temple and T. H. Chyba, National Council of Undergraduate Research Annual Meeting, Missoula, Mt., April 28, 2000.
- "A Compact Ozone DIAL System," T. H. Chyba, T. Zenker, **R. Payne, C. Toppin, B. Thomas,** D. Harper, N. S. Higdon, D. A. Richter, and J. Fishman, 20th International Laser Radar Conference, Vichy, France, July 10-14, 2000.
- "The Center for Lidar and Atmospheric Sciences Students Scanning Aerosol Lidar," T. H. Chyba, D. A. Temple, S. Bailey, A. Bowman, A. Omar, **B. Bradley, M. Edmondson, A. Futrell, C. Glenn, D. Harper, L. Haughton, S. Lee, K. Lewis, C. Meyer, R. Patterson, R. Payne, K. Reaves, L. Samuel, L. Williams,** N. S. Higdon and D. A. Richter, 20th International Laser Radar Conference, Vichy, France, July 10-14, 2000.
- "The CLASS Project," D. A. Temple and T. H. Chyba, NASA MUSPIN 10th Annual Conference, Atlanta, Ga., Sept. 11-14, 2000 (invited oral paper and poster).

Publications in Refereed Conference Proceedings:

- "Tests of a compact lidar for global monitoring of tropospheric ozone", T. H. Chyba, T. Zenker, **R. Payne, C. Toppin, M. Edmondson, K. Lewis,** D. Harper, N. S. Higdon, and D. A. Richter, and J. Fishman, in Environmental Monitoring and Remediation Technologies II, Proceedings of the SPIE, Vol. 3853, 94-100 (1999).
- "Tunable UV generation with a frequency-mixed Type II OPO," D. A. Richter, W. D. Marsh, N. S. Higdon, T. H. Chyba, and T. Zenker, Proceedings of the IEEE Aerospace Laser Conference, CD-ROM (2000).

Appendix 1. Copy of the article published in the Proceedings of the IEEE Aerospace Laser Conference

Appendix 2. Copy of the article published by S. Moody in Photonics Spectra

Appendix 3. Copy of the paper accepted at the 20th International Laser Radar Conference on the ozone lidar system

Appendix 4. Copy of the paper accepted at the 20th International Laser Radar Conference on the CLASS aerosol lidar system

In Proceedings of the IEEE Aerospace Laser Conference, Big Sky Montana, March 20-24, 2000

Tunable UV Generation with a Frequency-mixed Type II OPO[1]

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Abstract—Remote measurements of atmospheric gases such as ozone from airborne and ground-based platforms are currently made with a wide variety of UV laser sources. The capabilities of these existing systems could be significantly enhanced if compact, efficient, reliable, high peak power, tunable solid state laser sources could be developed. Such developments would also enable these systems to be deployed in small aircraft or on orbiting space platforms.

We have produced 38 mJ pulses of UV laser radiation with a frequency-mixed Type II KTA OPO in the 290-300 nm region. The OPO exhibits 42% slope efficiency. The entire transmitter fits into a lidar transceiver package consistent with the size constraints of an Unmanned Aeronautical Vehicle (UAV). The conversion efficiency from 1064-nm pump to 300 nm for this laser system (7%) is among the highest reported, to our knowledge.

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1. INTRODUCTION

Ozone is an atmospheric gas of crucial importance to the earth's environment. In the stratosphere, it shields life on the surface from harmful ultraviolet radiation and has a significant role in warming the earth's atmosphere. The international efforts to protect this stratospheric layer have led to several world-wide agreements with significant global economic impact due to the resulting changes in technologies incorporated into industrial processes and commercial products.

In the troposphere, ozone is a hazardous pollutant. It is produced in the northern hemisphere primarily from emissions from industries and automobiles. In 1997, the EPA estimated that it is a serious health concern for up to 46% of the U.S population [1]. When transported to rural and agricultural areas, increased ozone levels lead to the increased susceptibility of plants to disease, crop damage and reduced plant growth and productivity [2]. The EPA calculated that the higher air quality standards it proposed in 1997, if enforced, would reduce agricultural losses by $1 billion/year and reduce the number of cases of seriously impaired respiratory function by 1.5 million/year. It estimated the cost of compliance to be $8.5 billion [1].

In the southern hemisphere, comparable ozone levels can be generated through biomass burning [3]. The environmental consequences of pollution produced by increased industrialization in developing countries have the potential to be serious both to their own populations and agricultural production as well as a source of tension with other nations [4,5]. Scientific studies indicate that tropospheric ozone is increasing globally [3].

In addition to these direct effects, tropospheric ozone has a central role in the production of the OH radical, a powerful oxidizing agent. OH controls the concentrations of methane and other tropospheric gases; consequently global tropospheric chemistry can be affected by changing ozone levels. To address these concerns, the Global Tropospheric Ozone Project (GTOP) is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project [3]. The goals of GTOP are to understand the processes that control the global distribution of tropospheric ozone, disseminate this information and help formulate effective international policy.

[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

At present, ozone is monitored at ground level by a network of approximately 500 point sensors throughout the U.S. These sensors are only capable of quantifying ozone levels at their fixed locations. Regular (once every several weeks) balloon-borne ozone-sonde launches occur at perhaps 30-50 stations worldwide. These sensors provide detailed vertical distributions, but are too expensive (~$1000 total launch cost) for even daily launches and do not directly provide information on 3-dimensional distributions or transport.

Lidar systems can provide the high temporal and spatial resolution needed for detailed studies of ozone distribution and transport. There are approximately 20 ground-based ozone lidar systems throughout the world; about half of these are mobile. Several airborne ozone systems exist and a space-based system, ORACLE (Ozone Research with Advanced Cooperative Lidar Experiments), is being developed by NASA in collaboration with the Canadian Space Agency [6]. Current lidar systems, however, are typically extremely expensive, large and electrically inefficient and technically complex. These technical barriers limit their widespread use and, with a few exceptions, prevent routine deployments in small platforms such as satellites or Unmanned Aeronautical Vehicles (UAV's). For the most part, these limitations are due to current UV laser technology.

To address these technical limitations, we have developed a compact, ground-based, portable, eyesafe prototype lidar instrument for ozone measurements using the differential absorption lidar (DIAL) technique. The system incorporates (1) a compact transceiver module, (2) efficient OPO transmitter, (3) highly efficient, narrow-bandpass receiver, (4) user-friendly control software. In this paper, we will describe the lidar system in general to provide the context for our laser research but primarily emphasize the latter.

2. Compact Ozone Lidar System

A major technical barrier to be overcome in this research project is for the differential absorption lidar to be compact and portable. Figure 1 is a photograph of the system structure. The wheeled structure supports the transceiver box, the laser power supply, its water to air heat exchanger, electronics and the data acquisition computer. The transceiver box is a lightweight carbon fiber structure, compatible with the packaging limitations of a UAV platform. It can be manually pivoted and locked to vary the pointing direction. Computer-controlled scanning capability along one axis would be straightforward to implement in future systems. The telescope optics are located in the central compartment of the transceiver box, the laser transmitter is fully integrated in one of its two side compartments and the filtering optics and detectors are in the other one (figure 2). The transceiver can be oriented horizontal with either side facing up to access either side compartment. This is illustrated in figure 3, which is a downlooking view of the transmitter compartment with the cover removed. The Nd:YAG pump laser is at the bottom center of the compartment.

The Perseus B UAV available for missions through AURORA Flight Sciences is a propeller-driven aircraft with maximum altitude of 65,000 ft (20 km) [7]. It can supply 1.2 kW electrical power to the payload during the climbing and cruising portions of its flight. The payload is mounted in a pod in the nose of the aircraft. The maximum payload mass is 150 kg (330 lbs). Flight duration depends upon

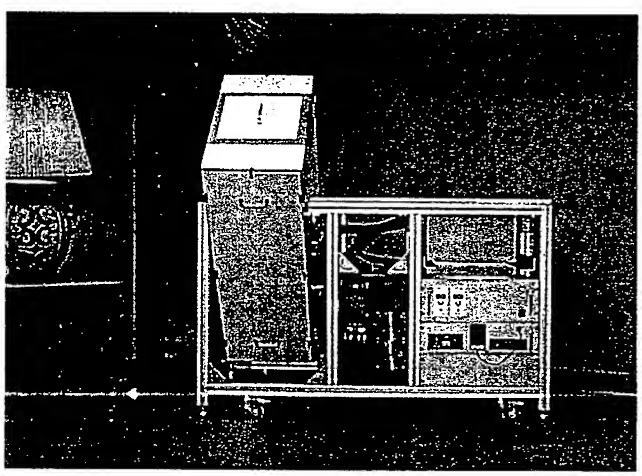

Figure 1: The lidar system structure with the pivoted transceiver module.

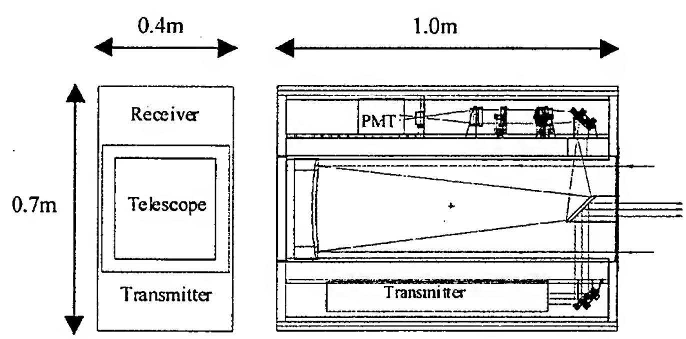

Figure 2: Schematic of the transceiver module.

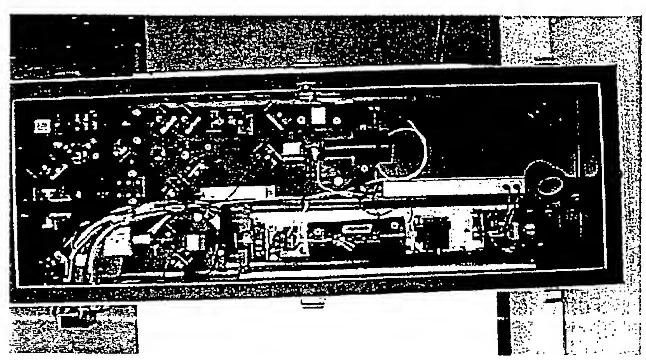

Figure 3. A down-looking view of the laser transmitter compartment with the transceiver module oriented horizontal.

payload mass and altitude; for a 150 kg payload, a 9 hour flight at 10 km is possible. Payload volume is 0.7 m^3.

The ozone transceiver box alone weighs only ~125 lbs and occupies 40% of this maximum payload volume, leaving sufficient space and weight available to accomodate the power supply, heat exchanger and control electronics. The electrical power constraints, however, are marginal with present commercial flashlamp power supplies. Assuming a 1% wallplug efficiency for the laser described in section 5, ~1 kW alone is required, leaving insufficient power for the remainder of the electronics. Therefore, in order for this system to be compatible with the Perseus B platform, either the laser power must be reduced or an increase in laser efficiency must obtained either through custom power supplies or through the incorporation of a diode-pumped source.

The payload capabilities of the Aurora Chiron UAV are similar to those of the Perseus B, though its maximum altitude and range is signficantly less. The Aurora Theseus B UAV is a twin engine aircraft which can support three pods each of which is equivalent to the Perseus B payload pod. Therefore, this platform has adequate power for the present instrument.

3. Lidar Receiver

The lidar receiver utilizes a 12" square parabolic primary mirror (Figure 2) and a grating-based spectrometer as a wavelength filter. The optical layout of the receiver system has been presented elsewhere [8,9]. Daylight prefiltering is performed by reflective dielectric coatings on the primary mirror and on the fold mirrors before the grating. The +1 and –1 orders of the grating provide the far and near field channels, respectively. With commercially available dielectric coatings, the throughput efficiency from the atmosphere to the detector plane is calculated to be ~60% for the far field (photon-counting mode) channel. The near-field (analog-mode) channel utilizes the negative first order reflection from the grating. With this configuration, the near field channel does not reduce the efficiency of the far-field channel.

Due to the anamorphic properties of the grating, the image of the field stop in the focal plane of the grating is an ellipse with a major diameter equal to 1.5 mm. A field mask is placed in the focal plane with four elliptical apertures centered at the locations of the on-line and off-line wavelengths for the near and far field channels. For stock commercial triplet lenses and gratings, the bandpass in the focal plane of the grating is computed using a commercial raytracing program to be 2.6 nm (FWHM) for a single wavelength channel. We have verified the bandpass in the laboratory with a custom collimated light source consisting of a fiber-coupled white light source and a 16" collimating telescope assembly. The measured bandpass has a FWHM equal to 2.4 nm, in excellent agreement with the raytracing calculation. This bandpass can be maintained for a multiwavelength system by opening a shutter in the focal plane of the grating in synchronization with the laser emission, thereby opening only the aperture corresponding to the transmitted wavelength.

4. Frequency-doubled Type II OPO

Advances in tunable Optical Parametric Oscillator (OPO) technology over the past three years have improved the efficiency and beam quality of these compact laser sources, especially in the ultraviolet. Wu, Blake, and coworkers at CalTech have demonstrated the crucial advantages of Type II OPO's: extremely narrow linewidth (1-2 cm^{-1}) and low divergence [10]. The result of this high beam quality output is that very high efficiencies (up to 48%) are possible in the

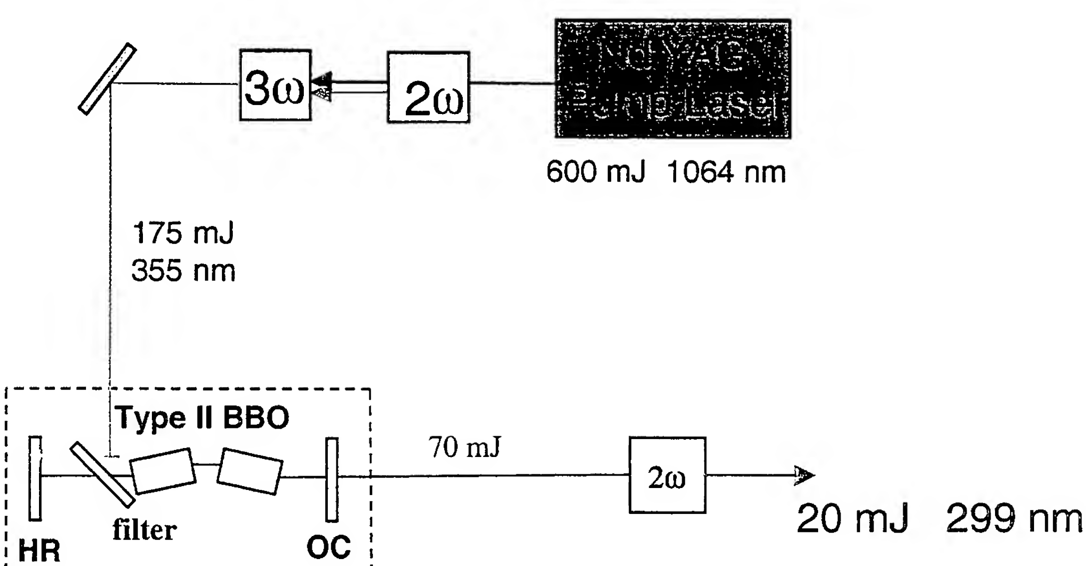

Figure 4. The 355-nm pumped, frequency-doubled Type II OPO

subsequent nonlinear doubling or mixing processes that are required to achieve UV wavelengths. Although the 355-nm pump-to-OPO output efficiency is not extremely high (25%), the high quality output beam recovers overall efficiency by providing very high conversion in these later processes. Still, overall optical conversion from 1064 nm to UV is at best only 3% and for the wavelength interval of interest for ozone measurements (290 nm to 300 nm), the conversion efficiency is only ~2%, yielding pulse energies of ~10 mJ with their pump source. By comparison, efficiencies of dye laser systems producing wavelengths suitable for ozone measurements are typically 4 to 5%.

Nevertheless, to meet our project goals, there are obvious practical advantages to an all-solid state laser system over a dye laser system. We therefore began our OPO investigations by repeating the experiments of Wu and coworkers, but with a more energetic pump source in order to produce higher pulse energies in the 300-nm spectral region. The experimental setup for the Type II BBO OPO is shown in Figure 4. An injection-seeded Nd:YAG laser produces 600 mJ pulses which are frequency-tripled to provide 175 mJ pulses at 355 nm to pump the OPO. The resulting 70 mJ pulses from the OPO are frequency-doubled to produce 20 mJ pulses at 299 nm. This final doubling efficiency (29%) is significantly less than that achieved by Wu et al. at this wavelength (43%), indicating that further optimization of our system may be possible. The linewidth of the uv output was below the resolution of our spectrometer, which is 0.2 nm. When the same OPO is pumped with the pump laser operating in a non-injection-seeded mode, only 10mJ of uv energy results. The temporal pulse lengths of the unseeded and seeded pump laser are 6 ns and 8 ns, respectively, and the corresponding OPO pulse lengths are 5.5 ns and 6.5 ns.

While this technique produces sufficient energy for our lidar system, it has several disadvantages, notably its need for a fairly large injection-seeded pump laser and that the OPO must be directly pumped in the uv with substantial pump pulse energies. Since the pump beam is reflected back out of the OPO towards the tripler, the output face of the tripler is damage-prone. Optical isolators operating at 355nm are available, but optical throughputs are only ~80%. Without an isolator, if the pump beam is pointed at a slight angle to prevent a direct back reflection, the OPO tends to operate at two wavelengths simultaneously. These considerations led us to consider a frequency-mixing approach rather than a frequency-doubling approach to produce the needed UV pulse energies.

5. Frequency-Mixed Type II OPO

Earlier innovative work by Marshall and coworkers at Fibertek [11] and subsequent work at NASA Langley Research Center [12] demonstrated that frequency-mixing techniques can be used to efficiently produce tunable UV radiation from near-infrared OPO's.

While Marshall's technique demonstrated a remarkable 25% conversion efficiency from 1064nm to 289 nm, the pump source was a 2W, 80Hz, diode-pumped Nd:YAG laser. The resulting output power of 0.5 W at 289 nm corresponds to pulse energies of 6 mJ. (Our frequency-doubled OPO experiments yielded an average UV power of 0.4 W with a 20Hz, 12W pump laser.)

Subsequent work by Marsh and coworkers at NASA Langley [12] attempted to apply this technique to produce higher pulse energies. With a 1J, 10Hz pump source, 40 mJ pulses were demonstrated at 289 nm (4% conversion efficiency).

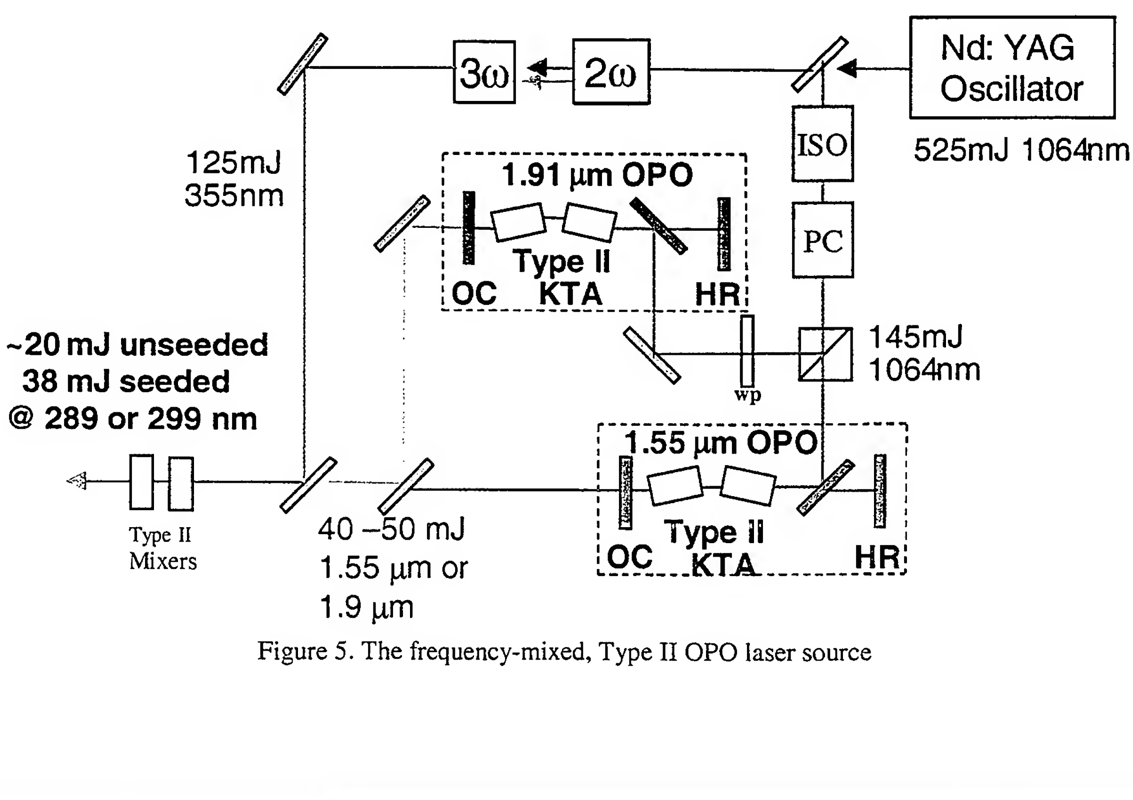

Figure 5. The frequency-mixed, Type II OPO laser source

In this paper, we review our current results from experiments in which we efficiently produce UV laser radiation with an OPO-based system building upon these earlier techniques. The fundamental wavelength from an injection seeded, 20Hz, Nd:YAG laser is split between pumping singly resonant Type II KTA OPO's in the infrared and a tripler stage for subsequent mixing with the outputs of the OPO's (Figure 5). By dividing the pump energy between the mixer and the OPO's, the risk of optical damage is significantly reduced. The OPO pump beam passes through an optical isolator and a Pockels cell polarization switch. This switch allows the user to control which OPO receives the full pump power on a shot-by shot basis. In this manner, the on-line and off-line pulse pattern for the DIAL measurement can be varied to test different averaging schemes. The OPO's are pumped by 145mJ and are operated at 1.55 and 1.91 microns. The pump beam diameter is 4 mm. In Figure 6, we present output energy from the OPO at 1.5 microns vs. input pump energy for the non-injection seeded case. The slope efficiency of the OPO is 42% and the overall conversion efficiency is 33%. The behavior of the 1.9 micron OPO is similar but with a slight reduction in both efficiencies by a few percent.

The remaining energy in the 1064 nm pump beam is frequency-tripled to provides approximately 125 mJ of UV into the mixer. The resulting UV output energies from the mixers have been measured to be approximately 38 mJ for both 289 nm and 299 nm, corresponding to an overall conversion efficiency of 7%. When unseeded, the uv output is approximately 20 mJ. The divergence of the uv output is approximately the same as the 355 nm beam (~1 mrad full angle) and the UV linewidth is under 0.2 nm (instrumentation limited). Figure 7 is a photograph of the transmitter in its final configuration with the beams drawn in for clarity.

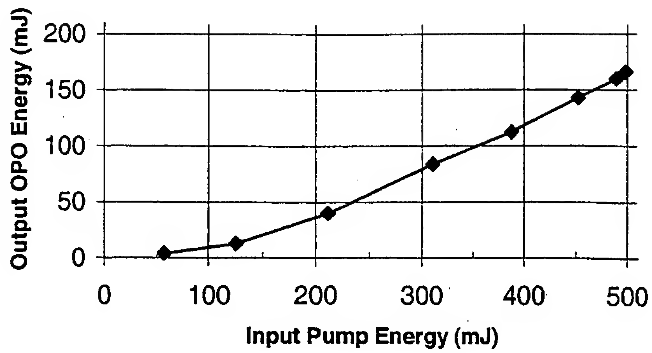

Figure 6. Output energy of the 1.5 μm OPO

Prior to transmission from the lidar system, the uv beam is expanded to be eyesafe. In order for the system to be eyesafe at zero range, the output pulse energies are limited to 16 mJ for a 2 inch diameter beam. Therefore, the laser source for the lidar system need not be injection-seeded for this ground-based application, significantly reducing the cost and complexity of the transmitter. While this absolute eyesafety requirement limits the peak pulse power, the average power can be significantly increased within this limit. To this end, future improvements will include increasing the pulse repetition rate while maintaining the zero-range eyesafety requirement. In a UAV application, eyesafety at zero range is not required and injection-seeding the pump laser is a significant advantage.

Preliminary exploratory experiments at NASA Langley have

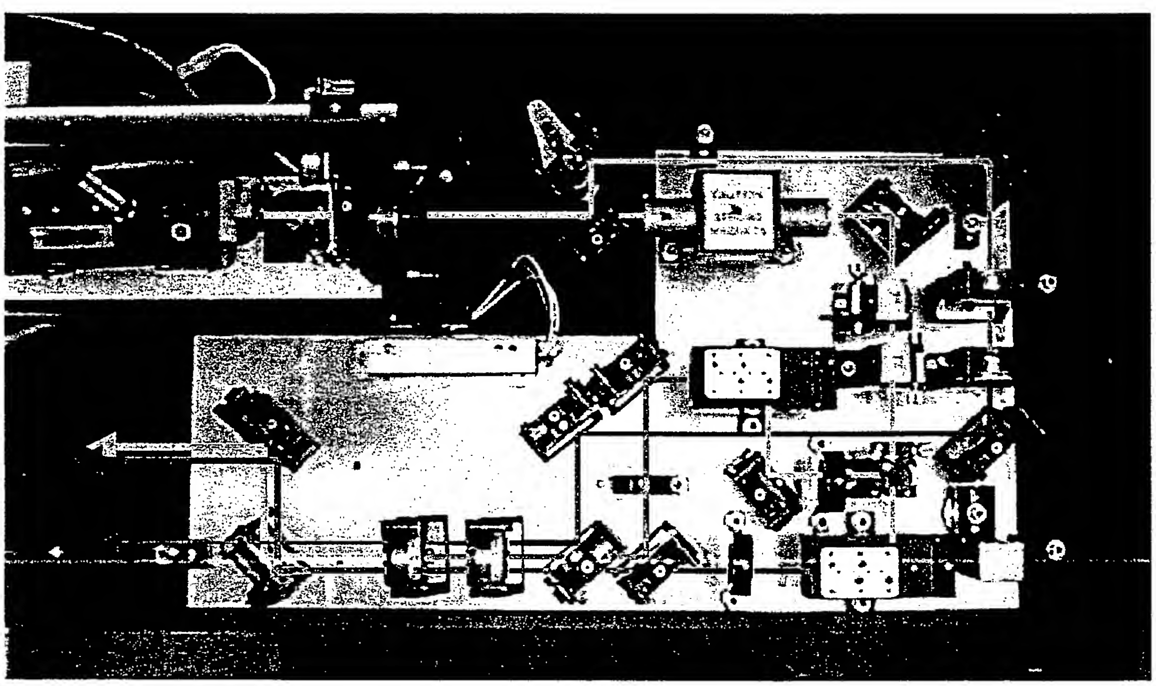

Figure 6. The compact breadboard OPO transmitter with the laser beams marked.

demonstrated that this technique can be scaled to produce UV energies in the 100 mJ range using a 1.2-1.5 Joule/pulse pump source [13].

The capabilities of a UAV ozone lidar system based on this technology compare favorably to those of existing airborne systems and are therefore adequate for a first generation lidar. The output UV energy of this laser is comparable to that of those currently used in a state-of-the-art NASA airborne ozone lidar system [14]. However, the NASA system employs two independent lasers to produce closely spaced on-line and off-line pulse pairs. While the average UV power of our lidar is therefore only half of that produced by this system, the optical efficiency of our receiver recovers this factor of two. The NASA ozone receiver employs a single 10-nm broad filter to pass both on-line and off-line wavelengths; the narrow bandpass of the grating-based receiver in our system reduces the optical background by an additional factor of 4. Having closely spaced (~300 μs) on-line and off-line pulse pairs in a high speed airborne platform insures that each pulse in the pair sees the same atmospheric absorption and scattering characteristics. If this should be needed for the lower speed UAV platform, a power supply capable of double-pulsing the Nd:YAG laser could be incorporated as is done in the LASE (Lidar Atmospheric Sensing Experiment) airborne water vapor lidar system [15].

6. Conclusions

In this paper, we have described our development of an efficient, high peak power laser source based on optical parametric oscillators for the generation of UV wavelength pairs suitable for DIAL measurements of atmospheric ozone. We have demonstrated 7% efficient conversion from the fundamental to the UV with a frequency-mixed Type II OPO when pumped by an injection-seeded laser source. The laser source has several significant advantages over other lasers currently used for ozone lidar systems. Its capabilities are adequate for the first generation, ground-based compact, eyesafe ozone lidar system we are currently testing. Except for the electrical power requirements of the current flashlamp power supply, this lidar system meets the payload constraints of the Perseus B UAV platform. Its performance characteristics are comparable to those of existing airborne ozone DIAL systems. Field performance and reliability of the complete system will be evaluated this year. This laser technology shows promise as a step leading to higher power compact laser sources for remote sensing systems deployed on small aircraft or satellites.

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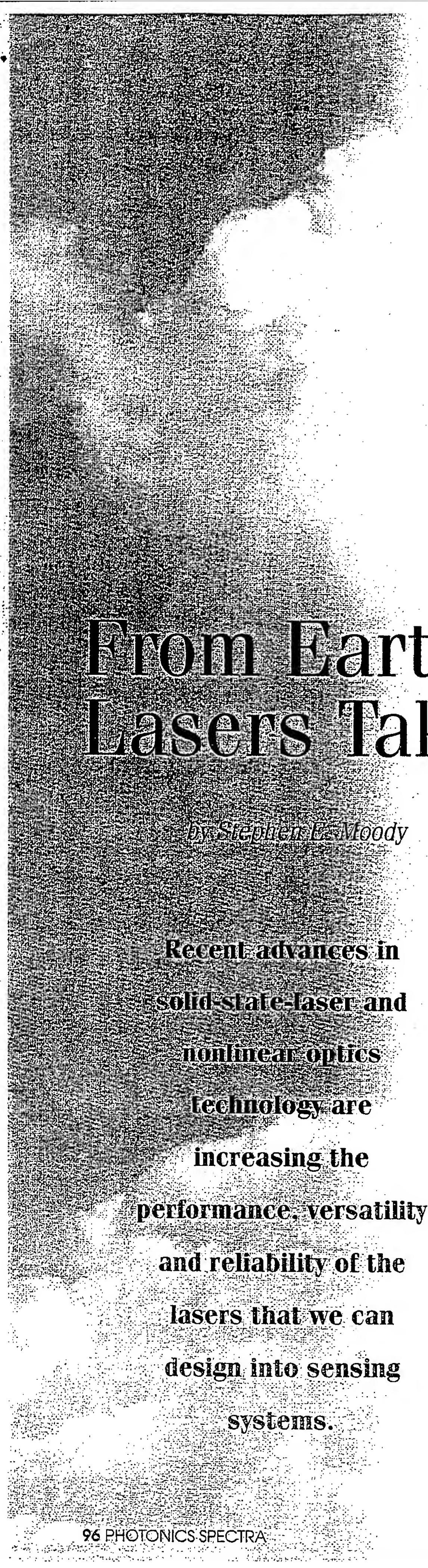


From Earth to Space, Lasers Take on Pollution

by Stephen E. Moody

Recent advances in solid-state-laser and nonlinear optics technology are increasing the performance, versatility and reliability of the lasers that we can design into sensing systems.

The monitoring and management of air quality is of direct concern to everyone living in the industrialized nations of the world. The economic and social activities of a modern society lead to emissions from a multitude of sources that affect air quality. These emissions take the form of gases and particulates, both of which have well-documented effects on human, animal and plant health when levels are too high.

Air quality is a *distributed* problem. There are numerous sources of polluting emissions, especially when cars are entered into the equation. Once entrained by the atmosphere, pollutants move and are often chemically modified as part of the natural atmospheric circulation process. As a result, the relationship between source and effect is not always easy to establish.

Point measurements of emissions at the source, which are the primary basis of our current regulatory fabric for air quality, are not enough to fully characterize air quality in a particular region. Because these measurements provide no information about transport or atmospheric chemistry, they can't by themselves predict the air quality that will actually result from a given set of sources.

To surmount these limitations, various kinds of remote sensing have an important role to play. Remote sensing's ability to map the atmosphere over broad areas of space and time allows us to include the effects of transport and thereby to strike a better balance between cost and benefit as we make important decisions about the management of air quality.

Benefits of laser sensing

There are several techniques for remote sensing of the atmosphere. Passive spectrophotometric techniques are used for wide-area mapping of the atmosphere, especially from space. These techniques provide very wide, even global, coverage but rather limited spatial resolution, especially in height. Absorption and scattering from aerosols and clouds also limit their ability to probe near Earth's surface. These techniques have been extremely productive for fundamental atmospheric science and have had a significant role in environmental issues that play out on a large spatial scale, such as the depletion of stratospheric ozone. However, they have limited use in addressing air quality issues on the size scale of an urban basin or on a time scale of hours, rather than days or months.

On this smaller spatial and temporal scale, active remote sensing with lasers comes to the fore. With high-power pulsed lasers, lidar systems can measure over ranges of about 10 km, with spatial resolution of 100 m or less and time resolution of seconds or minutes. The very high spectral resolution that is available from lasers enables excellent discrimination of a single molecular species.

Air quality is greatly affected by particulates and aerosols. At low altitudes, particulates pose a direct health hazard; at higher altitudes, they affect radiative transfer, cloud formation and precipitation. Particulates and aerosols are also excellent candidates for lidar measurement. With a backscatter measurement using a simple fixed-frequency transmitter, researchers can acquire a wealth of information.

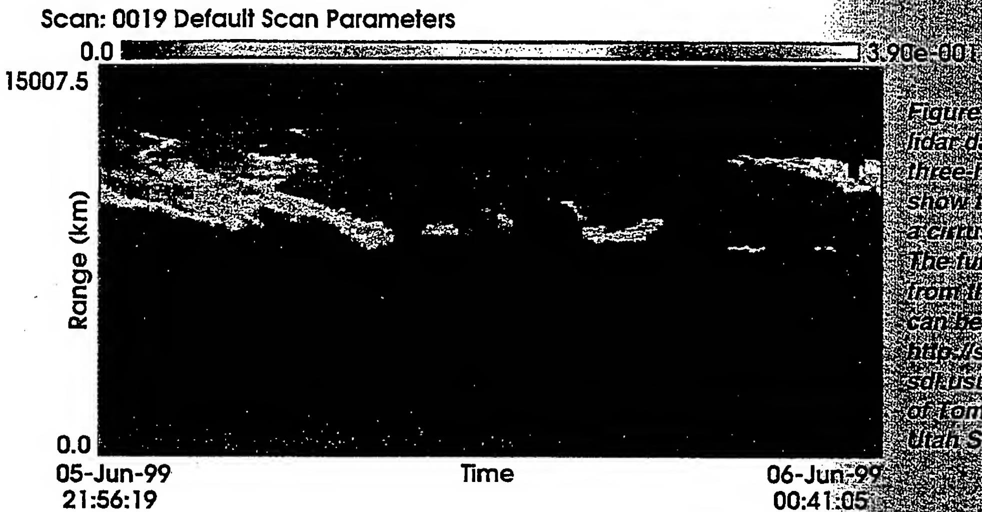


Figure 1. Aerosol lidar data for a three-hour period show the evolution of a cirrus cloud layer. The full data set from this campaign can be found at http://sweathog.des.sdl.usu.edu. Courtesy of Tom Wilkerson, Utah State University.

Tom Wilkerson and Jason Sanders of the Space Dynamics Laboratory at Utah State University in Logan operated the AROL-2 lidar system built by Orca Photonic Systems of Redmond, Wash., to acquire aerosol data (Figure 1). This system uses a flashlamp-pumped 532-nm Nd:YAG laser from Big Sky Laser Technologies Inc. of Bozeman, Mont. The data were collected during a measurement campaign this summer at St. Anselm College in Manchester, N.H.

Aerosol lidars from several institutions were operated in parallel to acquire a comprehensive data set covering a period of about one week. The AROL-2 was operated continuously in a vertical orientation. The plot, which represents a three-hour slice out of 10 days of essentially continuous data, shows time along the X axis, height along the Y axis and backscatter intensity encoded as color. The time evolution (via transport) of a cirrus cloud layer at an altitude of about 10 km is clearly visible. Although it is not shown in this plot, the lidar system also records depolarization data, allowing water and ice clouds to be distinguished.

Specific chemical species

With the rapid improvements in solid-state laser transmitter technology, it is now possible to deploy an aerosol lidar that can truly be a hands-off instrument.

Measurement of specific chemical species using this technique is considerably more challenging than aerosol monitoring. The most common technique used is differential absorption lidar, which requires that two pulses with slightly offset wavelengths be transmitted. One pulse is tuned to the center of an absorption line of the gas of interest, and the second is tuned to a nearby wavelength where absorption caused by the target gas is low. By comparing the returns for the two wavelengths, it is possible to derive the absorption along the path that is attributable to the target gas.

Differential absorption lidar has been successfully used in the UV/VIS region to measure gases such as NO_2, SO_2 and O_3. For the near-IR, NASA researchers have measured high-altitude water vapor from aircraft. A Raman lidar technique usually measures water vapor at lower altitudes because the absorption is too high for differential absorption lidar.

Tunable lasers are an absolute requirement for most differential absorption lidar systems. The system transmitter must be tuned to a pair of very specific wavelengths. With only a few exceptions, there is too little flexibility in the choice of wavelengths to allow fixed-frequency lasers to be used.

Requirements for an ideal transmitter would be high pulse energy, relatively short pulse length, narrow spectral bandwidth and broad tunability to allow the measurement of multiple species with a single system. Compactness, cost and reliability are also very real factors in achieving broader acceptance of lidar as a monitoring technique.

The traditional workhorse lasers for differential absorption lidar have been laser-pumped dyes, Ti:sapphire and, for some applications, alexandrite. All of these lasers fall short of ideal in one way or another.

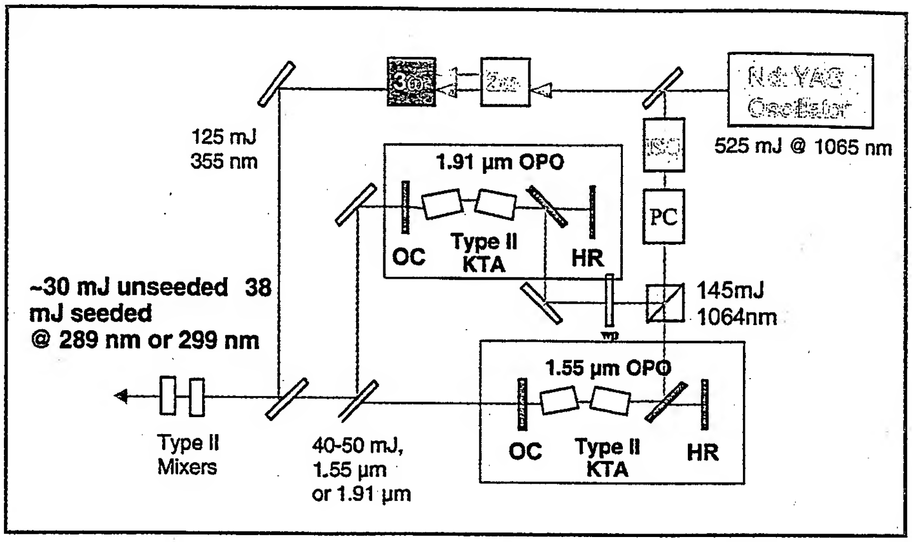


Figure 2. For lidar measurements of ozone, two low-energy optical parametric master oscillators provide the "on" and "off" wavelengths needed for differential absorption lidar. The output is upshifted to the UV region by mixing with energy at 355 nm taken from the Nd:YAG pump laser. The result is a compact, all-solid-state differential absorption lidar transmitter for ozone measurements. Courtesy of Thomas Chyba, Hampton University.

The advent of tunable optical parametric oscillator (OPO) technology is opening important opportunities for differential absorption lidar system designers. The combination of a tunable OPO with various stages of frequency multiplication and mixing leads to the availability of tunable radiation at nearly any wavelength, from the mid-UV to the mid-IR, in an all-solid-state package.

Because OPO technology is advancing rapidly, only a few lidar systems using these devices have been built. One is an H_2O device built by Gerhard Ehret and his colleagues at DLR, the German space agency in Cologne. Another is a compact ozone system integrated by assistant professor of physics Thomas H. Chyba and his co-workers at Hampton University in Hampton, Va., and ITT Industries Inc.'s Systems Div. in Albuquerque, N.M., with support from NASA.

Ozone is a particularly good candidate for a lower-cost, compact lidar system. It is not emitted directly, but rather created in a sun-driven photochemical process. The species that feed this process originate largely from motor vehicles and are therefore geographically dispersed. As a result, it is extremely difficult to predict the behavior of ozone in urban basins based on source data alone.

The Hampton University group's dual-wavelength OPO transmitter system is pumped by a single flashlamp-pumped Nd:YAG laser (Figure 2). The KTA OPOs use Type II phase matching based on innovative work by Geoffrey A. Blake, Sheng Wu and co-workers at the California Institute of Technology in Pasadena. Two distinct OPOs operate on alternate pump pulses to generate the two UV wavelengths needed for the ozone measurement. The output of the two devices is upconverted to the UV by mixing with tripled output from the same pump laser that drives them. This produces a compact, all-solid-state transmitter that can become the heart of a relatively small and inexpensive ozone lidar for urban-scale ozone surveys (Figure 3). Testing of the complete lidar system built around this transmitter is under way.

The OPO/mixing technology for tunable transmitters can also be extrapolated to much higher performance. William C. Edwards and Larry B. Petway at the NASA Langley Research Center in Hampton, Va., have demonstrated 160 mJ of tunable UV laser energy at 320 nm using a similar approach. To our knowledge, this is the highest tunable energy ever demonstrated in this spectral region, surpassing previous work by a factor of two.

The laser system consists of a frequency-doubled Nd:YAG laser that pumps a BBO OPO, followed by sum frequency mixing to yield the 320-nm wavelength. The UV output has a linewidth of 50 pm and pulse width of 16 ns. This new technology will be incorporated into a space-based differential absorption lidar system operating at 308 and 320 nm that will be used to measure stratospheric and tropospheric ozone on a global scale.

Applications for these systems are limited in part because only a few atmospheric gases absorb in the UV and visible region. The mid-IR region offers a much richer spectroscopic pallet, and many important measurements could be made if suitable lasers were available. However, until now there has really not been a general-purpose tunable laser for the mid-IR

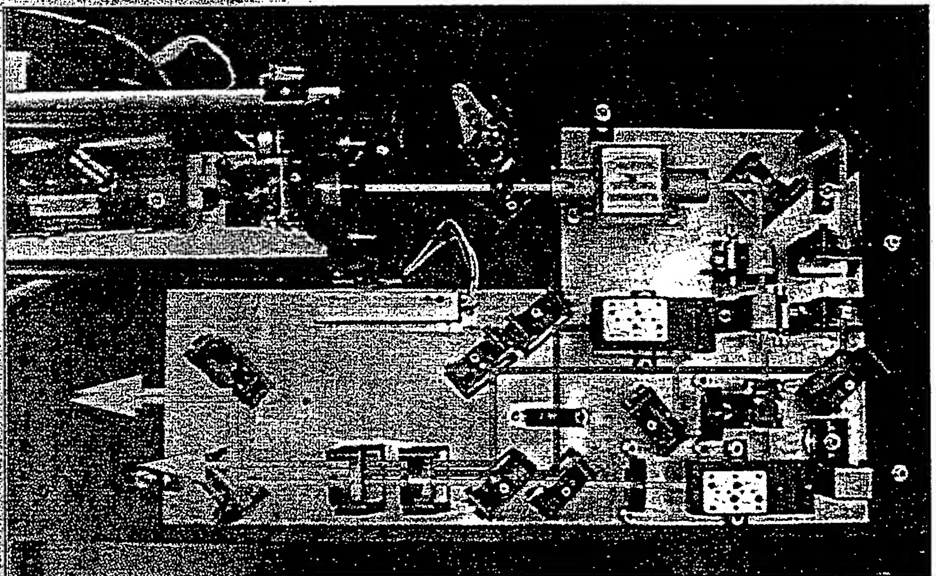


Figure 3. The OPO differential absorption lidar transmitter system is very compact. The laser beams are drawn in. Courtesy of Thomas Chyba, Hampton University.

that would meet the needs of differential absorption lidar applications.

A group led by Peter Woods at the National Physical Laboratory in Teddington, UK, has built a lidar with a low-energy transmitter based on difference frequency mixing. Even with the limited transmitter energy, this system has shown exciting capability to detect gases such as hydrocarbons in the mid-IR. However, OPO technology now offers broad access at relatively high power to the mid-IR region, opening a large set of new differential absorption lidar applications.

Lidar is not the only application of lasers to remote sensing. Low-power (usually continuous wave) lasers can monitor trace species by making measurements over a fixed, closed path. Typically, a laser spectrometer with both transmitter and receiver is used at one end, and a passive retroreflector at the other. The relevant spectral region for this kind of measurement is the IR region from 1.5 to 12 µm, where there is a very rich selection of molecular absorption features, including nearly every molecule of atmo-spheric interest.

Similar fixed-path sensing instruments with conventional light sources are used widely in industry and, to a lesser extent, in environmental applications. Laser-based monitors offer the possibility of much larger path lengths and much higher detection sensitivity. The challenge will be affordable field laser-based sensors that offer enough spectral coverage for multiple species.

Supplementary method

In comparison with lidar, these path-monitoring systems provide much less spatial information. However, they cost dramatically less and the sensitivity can be very high. As a result, this kind of laser path monitoring system can be an extremely important adjunct to other measurements for environmental applications.

Industrial Emissions Pose Optical Difficulties

One environmental application of optical sensing that has proved successful is the analysis of car exhaust streams. Using essentially special-purpose "fixed path" monitors, researchers have shown the technique's ability to measure the main target pollutants at the exhaust pipe for highway-based studies.

Why, then, haven't comparable monitors emerged for industrial applications? In our opinion, there are several key reasons:

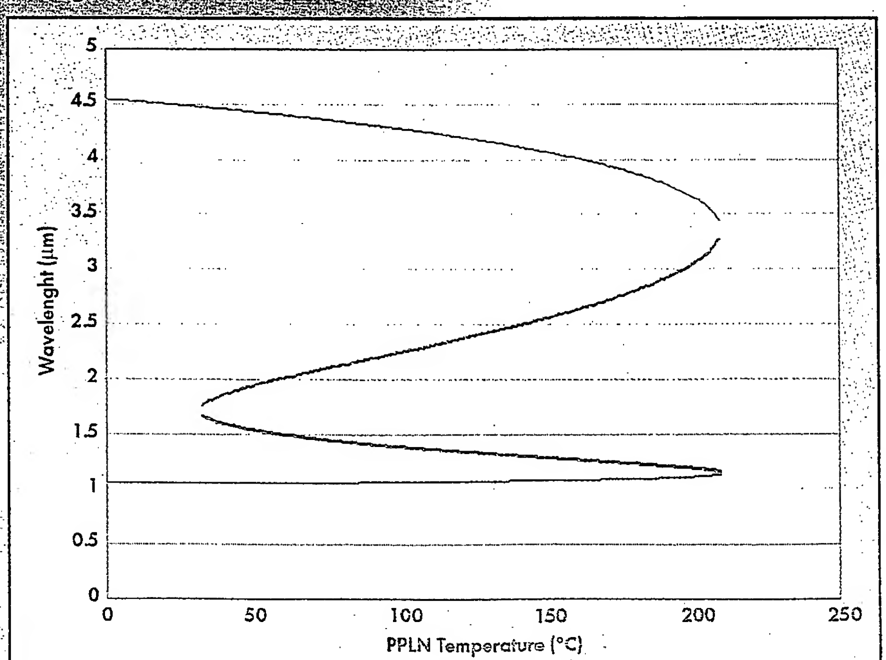
- Industrial emission monitor applications require measurement of a much wider range of gases than does automotive exhaust monitoring.
- The regulatory basis for industrial emissions is the mass emitted, whereas the regulatory basis for automotive exhausts is the density of pollutants in the exhaust plume, which optical sensors measure directly. Relating density to the mass emitted raises many difficult questions of data interpretation that industrial users prefer to avoid.
- Most industrial sites make measurements by removing gas from the stack and analyzing outside. This largely negates the advantages of optical sensing. Sensing "in the stack," on the other hand, raises reliability issues that must be solved by sensor manufacturers before users will adopt the technology.

SEM

The idea of laser path monitoring systems of this kind is not new. Fixed-path measurements were demonstrated more than 20 years ago with lasers such as CO_2 and with the 3.39-µm line of HeNe, which has a fortuitous coincidence with a methane absorption. More recently, sensors based on lead-salt diode lasers have shown high capability, although acceptance has been limited because of the need for cryogenics. For a few limited applications at short wavelength (<2 µm), room-temperature diodes provide a very low cost light source that makes an inexpensive and compact sensor system. However, the lack of a good narrowband, continuously tunable light source for the mid-IR region remains an impediment to the widespread deployment of laser path sensors.

Once again, OPO technology is at the threshold of making a difference. The advent of periodically poled lithium niobate material brings very high nonlinear gain all across the mid-IR region. As a result, it is possible to make continuous-wave devices that are pumped at very low power; for example, by a diode laser operating at a few hundred milliwatts. The tuning curves for periodically poled $LiNbO_3$ over a temperature range when pumped at 850 nm can be seen in Figure 4. As with all OPOs, wavelengths are emitted in pairs. This material has two stable operating points, which is the reason for four curves. With an appropriate resonator design, it is possible, at least in principle, to obtain output across the entire range of 1 to 4.5 µm.

Figure 4. The tuning curves for a periodically poled lithium niobate OPO with direct diode pumping in the near-IR show that over most of the temperature ranges, this material has two stable operating points, which are indicated by the bold and thin line weights. Courtesy of Angus Henderson, Aculight Corp.



The most difficult problem with these devices has been narrow banding and frequency control. Recent work in doubly resonant OPOs has shown that these problems can be overcome. At Aculight Corp. in Bothell, Wash., Angus Henderson and his colleagues have demonstrated continuous-wave IR output at the milliwatt level, with an effective bandwidth on the order of 10 MHz. Demonstrations of continuous tuning and detection of gases in the infrared with this new device are in progress.

Coming attractions

Remote sensing of the atmosphere has the potential to become an important tool toward understanding the atmosphere in support of air quality management. Techniques such as lidar have made major contributions to atmospheric research, but the high cost and complexity of these systems have led to very limited acceptance at the operational level.

Many factors contribute to the high cost and complexity of lidar and other laser remote sensing techniques. However, the limitations of current tunable laser technology have played a disproportionate role in hampering the acceptance of lidar by the air quality community.

Recent advances in solid-state-laser and nonlinear optics technology are increasing the performance, versatility and reliability of the lasers that we can design into sensing systems. Every step in this direction is a step toward wider acceptance of laser remote sensing. □

Lidar has made major contributions to atmospheric research, but the high cost and complexity have led to very limited acceptance at the operational level.

Acknowledgments

The author wishes to acknowledge useful discussions with David L. Cunningham (Orca Photonic Systems Inc.), Angus Henderson (Aculight Corp.), James Barnes and William Edwards (NASA Langley Research Center), Tom Wilkerson (Utah State University) and Thomas Chyba (Hampton University).

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A Compact Ozone DIAL System

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ABSTRACT

A portable, eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements is currently being tested. The instrument is designed to be as reliable and simple as possible but still be capable of routinely measuring ozone profiles with less than 10% relative error from the ground up into the lower stratosphere. Novel features it incorporates include an all-solid state OPO transmitter, a dual channel high efficiency grating-based receiver, a fast membrane mirror light shutter and mini-photomultiplier tubes. This lidar satisfies the basic requirements necessary for future global monitoring projects requiring multi-instrument networks, such as that proposed for the Global Tropospheric Ozone Project (GTOP). GTOP is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project to meet its goal to better understand the processes that control the global sources, sinks, and transformation mechanisms of tropospheric ozone.

1. Introduction

A portable, eye-safe, ground-based prototype instrument specialized for ozone differential absorption lidar (DIAL) measurements is under development and testing by Hampton University and ITT Industries with support from NASA and the DOD. The prototype instrument is intended to operate at remote field sites and to serve as the basic unit for future monitoring projects requiring multi-instrument networks, such as that proposed for GTOP. By tuning the transmitted wavelengths to reduce their absorption in the troposphere, it may be possible to probe into the stratosphere and thereby use such a network to monitor stratospheric ozone. The system incorporates (1) a compact all-solid state transmitter, (2) a highly efficient, narrow-bandpass grating-based receiver, (3) dual analog and photon-counting detector channels, and (4) flexible, user-friendly control software.

A goal of this effort is for the prototype system to lead toward a field-hardened, standardized, deployable system which can be duplicated for use by researchers in other nations in support of GTOP. We estimate the duplication cost of our system as ~$300k. A possible strategy for achieving this goal is to recruit faculty and students from other nations, provide on-site training with a duplicate instrument at Hampton University and return them with their instrument to their home institutions. In this way, an international network of ozone lidar stations could be developed, utilizing the existing infrastructure of educational institutions.

2. Lidar System Structure

A major objective of this project is for the lidar system to be compact and portable. Figure 1 is a photograph of the system structure. The structure supports the transceiver box, the laser power supply, its water to air heat exchanger, electronics and the data acquisition computer. The transceiver

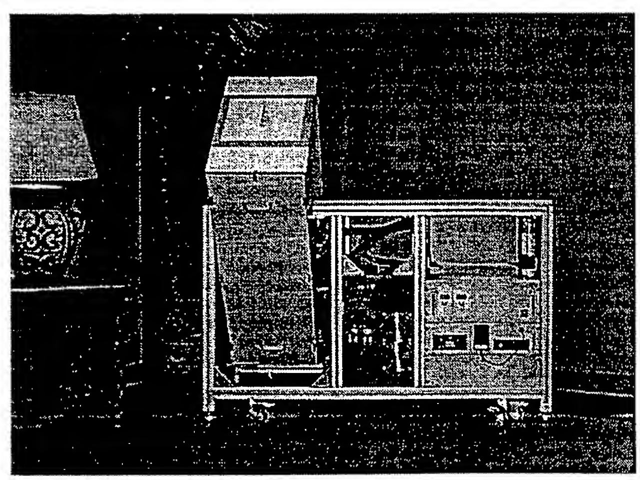

Figure 1. The lidar system structure with its pivoted transceiver module.

box is a lightweight carbon fiber structure. It can be manually pivoted and locked to vary the pointing direction. The primary mirror is located in the central compartment of the transceiver box, the laser transmitter is fully integrated in one of its two side compartments and the filtering optics and detectors are in the other one (Figure 2). Either side compartment can be oriented horizontally for maintenance.

3. Lidar Receiver

The lidar receiver utilizes a 12" square parabolic primary mirror and a grating-based spectrometer as a wavelength filter. Daylight prefiltering is performed by reflective dielectric coatings on the primary mirror, on the fold mirrors before the grating and by the specular reflection off the grating which is oriented normally to the incident beam. The +1 and −1 orders of the grating provide the far and near field channels, respectively. With commercially available dielectric coatings, the throughput efficiency from the atmosphere to the detector plane is ~60% for the far field (photon-counting mode) channel. The near-field (analog-mode) channel utilizes the negative first order reflection from the grating. With this configuration, the near field channel does not reduce the efficiency of the far-field channel.

Due to the anamorphic properties of the grating, the image of the field stop in the focal plane of the grating is an ellipse with a major diameter equal to 1.5 mm. A field mask is placed in the focal plane with four elliptical apertures centered at the locations of the on-line and off-line wavelengths for the near and far field channels. For stock commercial triplet lenses and gratings, the bandpass in the focal plane of the grating is computed using a commercial raytracing program to be 2.6 nm (FWHM) for a single wavelength channel. We have verified the bandpass in the laboratory with a custom collimated light source consisting of a fiber-coupled white light source and a 16" collimating telescope assembly. The measured bandpass has a FWHM equal to 2.4 nm, in excellent agreement with the calculation. This bandpass is maintained in our multiwavelength system by opening a shutter in the focal plane of the grating in synchronization with the laser emission, thereby opening only the aperture corresponding to the transmitted wavelength.

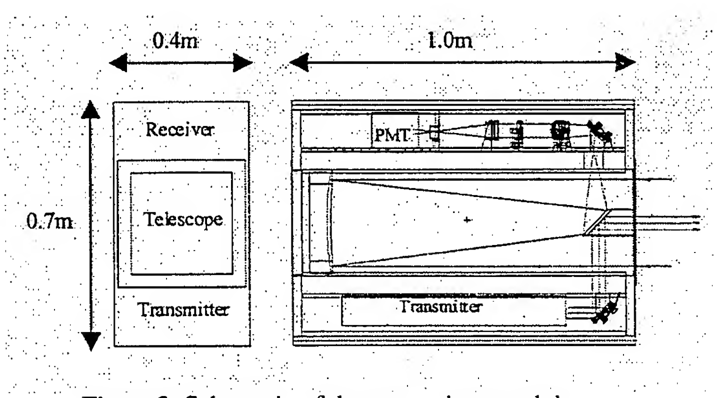

Figure 2: Schematic of the transceiver module.

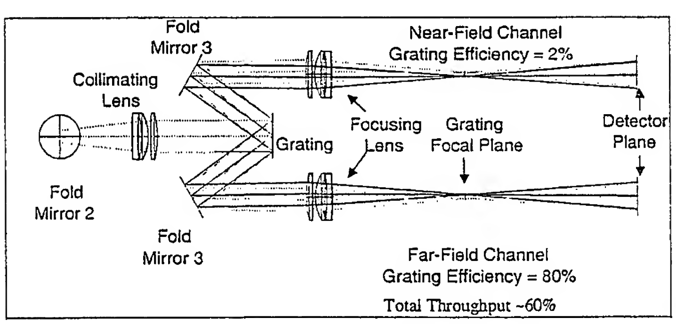

Figure 3. The grating-based receiver.

The detectors chosen for this system are 7400 series Hamamatsu mini-photomultiplier tubes mounted in modules supplied by Licel Corporation.

In order to prevent the strong near-field return from causing signal-induced-bias in the photon-counting channel, we have incorporated an electrostatically-deformable membrane mirror light shutter (Optronics, Inc.) into the receiver (fold mirror 3 in Fig. 3). Preliminary tests of this device in our system indicate that it provides an attenuation factor greater than 10^2 with a switching time under 1 μs. Final tests results will be reported at the conference.

4. Lidar Transmitter

The all-solid state laser transmitter for our system is shown as a photograph in Figure 4 and schematically in Figure 5. Our present transmitter is based on our own research on a number of candidate systems as well as previous techniques published by others (see references). The fundamental wavelength from a 20Hz Nd:YAG laser is split between pumping singly resonant Type II KTA OPO's in the infrared and a tripler stage for subsequent mixing with the outputs of the OPO's (Figure 5). By dividing the pump energy between the mixer and the OPO's, the risk of optical damage is low. The OPO pump beam passes through an optical isolator and a Pockels cell polarization switch. This switch allows the user to control which OPO receives the full pump power on a shot-by-shot basis. In this manner, the on-line and off-line pulse pattern for the DIAL measurement can be varied to test different averaging schemes. The OPO's are pumped by 145mJ and are operated at 1.55 and 1.91 microns. The pump beam diameter is 4 mm. The slope efficiency of the 1.55 micron OPO is 42% and the overall conversion

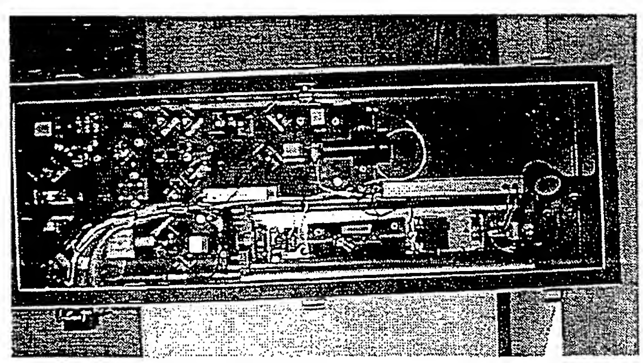

Figure 4. The OPO-based laser transmitter.

efficiency is 33%. The behavior of the 1.9 micron OPO is similar but with a slight reduction in both efficiencies by a few percent.

The remaining energy in the 1064 nm pump beam is frequency-tripled to provide approximately 125 mJ of UV into the mixer. The resulting UV output energies from the mixers have been measured to be approximately 38 mJ at either 289 nm or 299 nm, corresponding to an overall conversion efficiency of 7%. When unseeded, the uv output in either beam is ~20 mJ. The divergence of the uv output is approximately the same as the 355 nm beam (~1 mrad full angle) and the UV linewidth is under 0.2 nm (instrumentation limited). The pulse widths are ~7 ns.

Prior to transmission from the lidar system, the uv beam is expanded to be eyesafe. In order for the system to be eyesafe at zero range, the output pulse energies are limited to 9 mJ for a 1.5 inch diameter beam. Therefore, the laser source for the lidar system need not be injection-seeded for this ground-based application, significantly reducing the cost and complexity of the transmitter. While this absolute eyesafety requirement limits the peak pulse power, the average power can be significantly increased by increasing the pulse repetition rate. To this end, we are presently integrating a 300 mJ pump laser with a 30 Hz pulse repetition frequency into the transmitter. For this PRF, 8 mJ pulses are eyesafe at zero range. The nominal ocular hazard distance for this source operating at 15 mJ/pulse at 30Hz with a 1.5 inch diameter beam is only 50 m.

5. Performance Calculations

We have calculated the expected performance for our system using actual ozonesonde data sets and the receiver, transmitter, and data acquisition characteristics appropriate for our system. The signal to noise (S/N) ratio for the simulated DIAL return signals are calculated incorporating the contributions of several error sources: signal noise, sky background (30° zenith angle), dark current/counts of the PMT, A/D resolution, and dead time error. A S/N ratio of

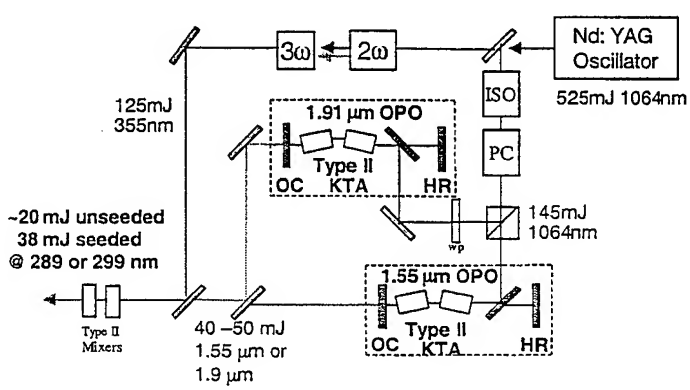

Figure 5. The 20 Hz PRF laser transmitter

better than 10:1 can typically be obtained in about 30 min and with only a few minutes averaging time for altitudes greater than 10 km and lower than 3 km, respectively. Measurements into the lower stratosphere are possible with this S/N with the far-field photon-counting channel. By choosing wavelengths optimized for the stratosphere, the S/N in this region can be improved. These calculations have been discussed in greater detail in the references.

6. Computer Data Acquisition System

The data acquisition and control hardware is integrated in a rack-mounted industrial PC. The detector channels utilize a 12-bit A/D card (Gage Corp., ISA1012) and a photon counting scaler card (Santa Fe Energy Research, MCS100). A Multi-function I/O card (National Instruments, PCI6110E) is used for digital and analog control signals and system timing. LabVIEW software provides a user-friendly graphical interface for instrument control, data acquisition, and online processing, including DIAL error analysis, Rayleigh corrections and false color plots of ozone concentrations.

ACKNOWLEDGEMENTS

Core funding for this project is from the NASA Minority University Research and Education Division (MURED) grants NAG-1-1949, NAG-1-2224, NCC-1-251 and a DOD Infrastructure Support Grant, FQ8671-9901183. We also are grateful for equipment loans and technical advice from Dr. Tom McGee at NASA Goddard and James Barnes and Waverly Marsh at NASA Langley. We also acknowledge internal R&D funding from ITT Industries, Systems Division. Ms. Payne is being supported through the Virginia Space Grant Consortium (VSGC) and the Office of Naval Research. Ms. Toppin is being supported through VSGC.

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The Center for Lidar and Atmospheric Sciences Students Scanning Aerosol Lidar

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ABSTRACT

A portable, eyesafe, 125 mJ, 20Hz, 1.5 micron scanning aerosol lidar system is being tested by the student lidar team in the Center for Lidar and Atmospheric Sciences Students (CLASS). Its purpose is to remotely detect aerosols, clouds, and pollution in the lower atmosphere. The CLASS project is a 5-year undergraduate research training project funded by NASA to educate students in atmospheric science and lidar technologies. In conjunction with engineers at ITT and NASA, the student lidar team has designed, constructed, and is currently testing the lidar. Present student research projects include: determination of the laser parameters to insure eyesafety, tests of the lidar system, mathematical models of the atmosphere and comparison with lidar performance, investigation of the health effects of fine particulates, determination of natural and anthropogenic chemicals in the local atmosphere, and the development of hardware and software to fire the laser, control the scanner and record, analyze, and display the atmospheric data.

1. Introduction

Laser remote sensing of the atmosphere can be a powerful motivational tool for science education. It connects a timely and compelling concern for the environment with cutting edge technologies. Its interdisciplinary nature enables students throughout the natural sciences and engineering to contribute their own unique training to a collaborative research project. Finally, laser remote sensing can be used to develop an awareness of the atmosphere as a shared resource and of the importance of continuing research to understand its behavior and the impact humanity's activities has upon it.

The Center for Lidar and Atmospheric Sciences Students (CLASS) project is sponsored by the NASA Minority University Research and Education Division with the goals of: (1) providing education and training in NASA-related technology and science to U.S. students who are underrepresented in these areas, (2) encouraging these students to achieve advanced degrees, and (3) integrating educational curriculum with research training.

CLASS addresses these goals in three distinct ways: (1) by assisting faculty to develop and assess new courses or course modules to expose a broad cross-section of students to optical remote sensing of the environment and the mission of NASA's Earth Science Enterprise; (2) by forming a student lidar team through which students receive in-depth training in these areas, interact with scientists and engineers from NASA and industry informally and through internships, design, build, test, and maintain a lidar instrument, propose, and perform experiments with that instrument, and analyze, interpret, and report the experimental results; and (3) outreach to K-12 through demonstrations, joint experiments, web-based learning exercises, and participation in the activities of the student lidar team.

In this article, we will focus primarily on the joint Hampton University-NASA-ITT design and testing of a portable, eyesafe, scanning aerosol lidar system to be used for student education, research training and outreach.

2. Lidar System Design Considerations

Perhaps the most conceptually simple lidar system is a single-wavelength elastic backscatter lidar. Despite this apparent simplicity, however, few portable, eyesafe, scanning lidar systems exist with sufficient pulse energies to make rapid 3-dimensional maps of the atmosphere. These capabilities consitituted the initial general design goals.

The choice of wavelength for the system and the corresponding laser and detector technology is based on several factors. The biology students on the team reviewed the literature on the health effects of fine particulates as well as the new PM 2.5 standards proposed by the EPA in 1997. Together with general considerations from Mie scattering theory, this suggested that shorter wavelengths were desirable

in order to be more sensitive to fine airborne particles. In order to evaluate different candidate laser sources, a physics student on the team encoded the ANSI eyesafety standard into a MathCAD program with a user-friendly interface. Much of the work on this program was accomplished during a summer industrial internship at ITT. Figure 1 is a plot of the maximum permissible exposure (maximum eyesafe energy) vs. output beam diameter at zero distance from the laser, assuming a 1.55 micron wavelength, 20 Hz repetition rate, and 6 ns pulse width. It indicates that pulse energies with energies as high as a joule are eyesafe (for unassisted vision) in the 1.5 micron spectral region with modest beam diameters. The program also computes the nominal ocular hazard distance as a function of several relevant laser parameters.

These considerations led to the choice of an OPO transmitter based on the same technology developed by ITT for the HU compact ozone system. A chemistry student utilized HITRAN to plot atmospheric absorption over an optimal subset of the tuning range of the OPO. This analysis led to the atmospheric transmission window at 1.5554 microns to be chosen for the OPO wavelength.

3. Lidar Transceiver

The lidar transceiver box designed by ITT is a lightweight (<25 lbs fully loaded) reinforced graphite epoxy structure with dimensions 12.5" x 12.5" x 16". It is shown in Figure 2 attached to a temporary mount which allows its pointing direction to be manually changed. The front compartment houses a 10 inch diameter primary mirror and detection optics. A cover on the rear of the unit can be removed to access the laser transmitter, as shown in Figure 3. The transceiver box is attached to the laser power supply and heat exchanger. A computer controlled scanning mount (not shown) made by Torus Technologies is currently being tested prior to integration with the lidar transceiver. This scanner enables lidar pointing throughout the full range of azimuthal and elevation angles with an angular resolution of 13 μrad and maximum scanning speed of 2 rad/sec.

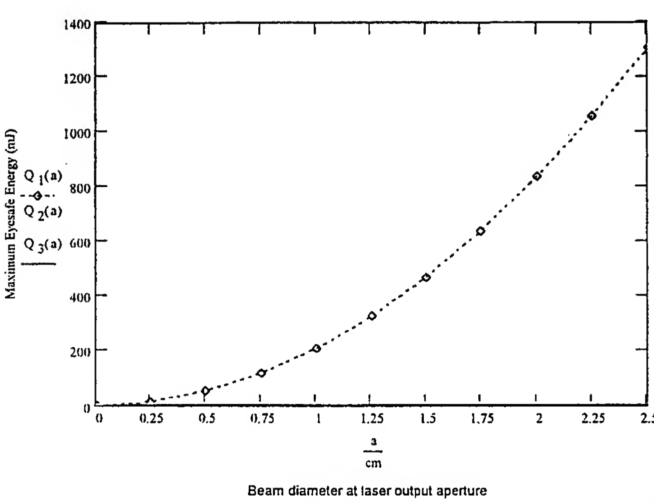

Figure 1. Maximum permissible exposure (MPE) vs. beam diameter at the laser output aperture.

4. Lidar Transmitter

The pump source for the transmitter shown in Figure 3 is a Continuum Nd:YAG pump laser folded into an angle to fit in the box. An optical isolator (upper center) protects the laser from optical reflections from the OPO (upper left corner). The Type II KTA OPO is shown schematically in Figure 4. Its output beam is into the plane of the figure in Figure 3 and its beam is expanded to reduce its divergence. The beam can be transmitted coaxially with the receiver using a fold mirror shown in the upper right corner of the transceiver box in Figure 2 to relay it to an upcollimating telescope housed in the central tubular obscuration. It can also be transmitted biaxially by replacing the fold mirror with a beam expanding telescope. Laboratory experimentation and a ZEMAX raytracing study are underway to evaluate the system response in both approaches.

Figure 5 is a plot of the measured OPO output energy vs.

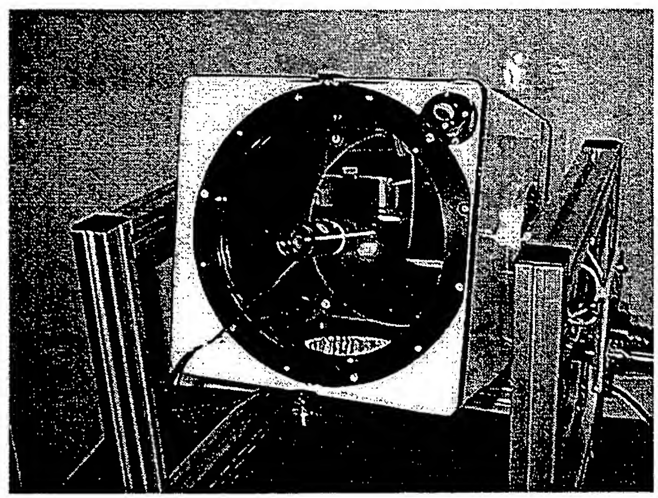

Figure 2. The lidar transceiver.

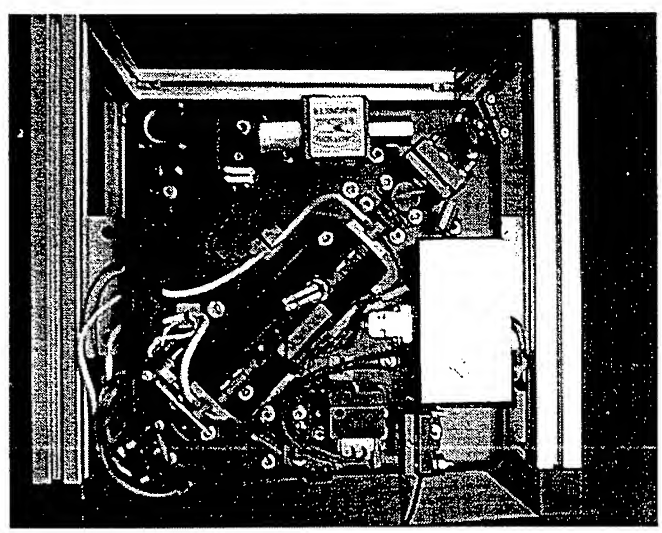

Figure 3. The 1.5 micron laser transmitter, accessible through a rear panel in the transceiver box.

pump energy at 20 Hz. The slope efficiency for the OPO is 35%. The characteristics of the laser transmitter are summarized in Table 1.

5. Lidar Receiver

A raytrace analysis of the receiver optical layout of the receiver was performed by an electrical engininеering student on the team during his summer internship at ITT. The final design arising from this analysis incorporates a series of lenses housed in the central 1.25" diameter tubular obscuration along with an optical filter for solar background rejection. These lenses collimate the beam reflected from the 10" primary mirror in order for it to pass normally through the interference filter and then focus it on the 200 micron-diameter active area of an EG&G C30662 series InGaAs APD. According to the ZEMAX raytrace analysis, the spot size of the beam on the detector plane from a source at infinity is 130 microns (for a 0.5 mrad receiver field of view). For a source at infinity, the optical throughput onto the detector active area is calculated by raytrace to be 98%, with the 2% loss arising from the central obscuration. This calculation does not take into account the expected ~70% transmission of the filter currently on order.

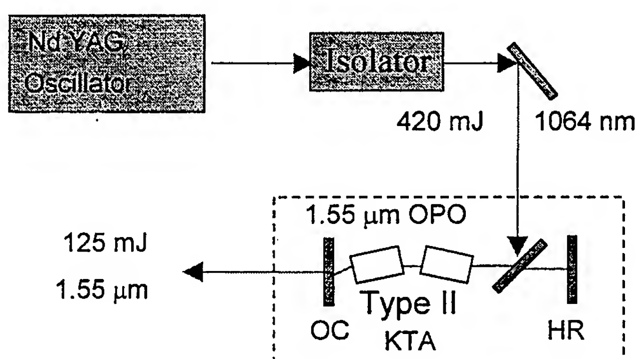

Figure 4. The eyesafe OPO transmitter.

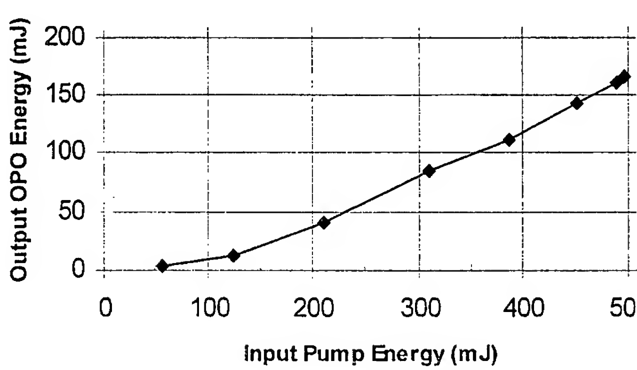

Figure 5. Conversion efficiency of the OPO transmitter.

6. Data Acquisition and Control

Control of the scanner, laser, and data acquisition system will be performed by a single computer utilizing LabVIEW. This software is currently under development by mathematics, computer science, and engineering students on the team.

7. Lidar Performance Modelling

Two mathematics students on the team are developing a lidar model written in MathCAD to understand and predict the system performance. This model incorporates all the relevant parameters of the laser, receiver and atmosphere. Figure 6 is a plot of the number of backscattered photons vs. altitude and horizontal distance for the system calculated with this model. The atmosphere is assumed clean except for a uniform aerosol layer between 800 and 850 m in altitude. This layer is characterized by a backscatter coefficient of 0.01 $km^{-1}sr^{-1}$ and an extinction coefficient of 0.1 km^{-1}. Currently, signal to noise considerations are being incorporated into the model as well as a more realistic overlap factor based on the results of the ZEMAX analysis.

Parameter	Pump Laser	OPO
Wavelength	1064 nm	1555.4 nm
Pulse Energy	420 mJ	125 mJ
PRF	20 Hz	20 Hz
Pulsewidth	6 ns	5.5 ns
Linewidth (FWHM)	0.11 nm	0.60 nm
Beam diameter	5 mm	2.5 mm x 4 mm
Divergence (full angle)	0.55 mrad	3 x 4.5 mrad

Table 1. Laser Transmitter Characteristics

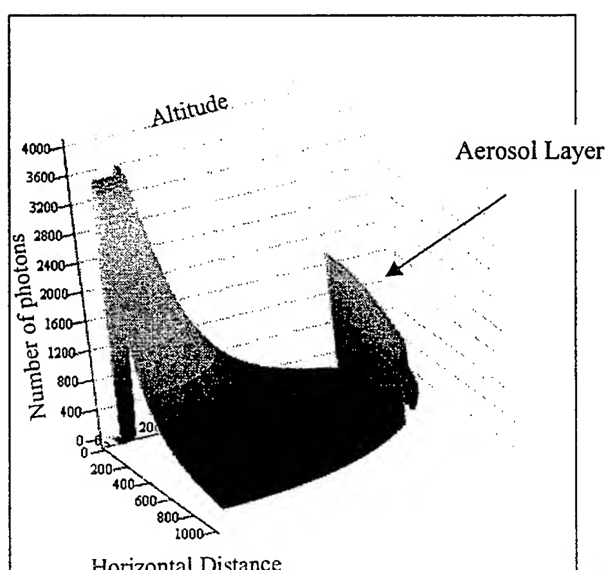

Figure 6. Calculated number of backscattered photons arriving at the telescope vs. altitude and horizontal range.

8. Educational Outreach

An important aspect of the CLASS project is educational outreach to college level students through summer programs and to primary and secondary schools students. The HU summer programs we work with include the NASA-funded AURORA (Advanced Undergraduate Research using Optical Radiation in the Atmosphere) and the NSF-sponsored UnIPhy-REU (Undergraduate Institute in Physics-Research Experiences for Undergraduates) programs. We have partnered with Crittenden Middle Magnet School (CMS) and Warwick High School (WHS) to develop an ongoing program to actively involve their students in our project. Our outreach efforts have included discussions of current topics in atmospheric science, the health effects of particulates and airborne toxins, web-based evaluations of local air pollution sources using the tool www.scorecard.org and EPA data bases, measurements of atmospheric particulates with particle counters, optics and laser experiments, joint experiments, lab visits and demonstrations.

The CLASS project also sponsors an annual 8 week summer internship through our industrial partner, ITT. This provides our students with hands-on work experiences related to the optical remote sensing projects underway at HU and at ITT.

ACKNOWLEDGEMENTS

Core funding for this project is from the NASA Minority University Research and Education Division (MURED) grant NCC5-348. The OPO laser system development has been supported by NASA MURED grants NAG-1-1949, NAG-1-2224, NCC-1-251, a DOD Infrastructure Support Grant, FQ8671-9901183 and internal R&D funding from ITT Industries, Systems Division. ITT also provides in-kind support for the summer internship program. Additional funding for the summer internship program has been provided by the Virginia Space Grant Consortium (VSGC). Ms. Payne is being supported through the VSGC and the Office of Naval Research.

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